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# Efficacy of in-furrow zinc phosphide pellets for controlling rodent damage in no-till corn

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**Abstract**

Plagues of rodents in field crops have been a problem of human societies for centuries. These problems diminished with the onset of effective herbicides and clean farming practices in the 1960s, but there has been a resurgence of rodent irruptions in cropfields since the advent of conservation tillage systems. We examined the efficacy of in-furrow applications of 2% zinc phosphide ($Zn_3P_2$) pellets (27.5 kg ha$^{-1}$ [5 lb acre$^{-1}$]) at planting for the control of rodent damage in no-till corn. Three independent field studies were conducted in northeastern NE, southern IL, and southern IN. Vole populations in the most severely damaged fields (IL) ranged from 104 to 138 active colonies ha$^{-1}$. $Zn_3P_2$ reduced yield loss in the three study areas by 7–34%. Projected economic returns ranged from US$1044 to US$5360, based on representative 64-ha fields and a net profit of US$250 ha$^{-1}$. Benefit:cost ratios ranged from 1.1 to 5.6:1 and were directly related to vole population levels. To prevent rodent damage in no-till cornfields, we recommend an integrated pest management approach that incorporates the use of a combination of the following techniques: rodent population monitoring, economic thresholds, mowing, early pre-plant herbicides, broadcast whole-kernel corn, and in-furrow applications of $Zn_3P_2$ pellets. 

*Keywords:* Conservation tillage; Corn; Economics; Efficacy; Field mice; No-till; *Microtus*; *Peromyscus*; Rodents; Voles; Wildlife damage management; Zinc phosphide

## 1. Introduction

Rodents have plagued human societies for centuries and have become a part of our culture, as is demonstrated by artistic representations of the 14th century Black Death, the statutory Danish Rat Law of 1908, and the mythical Pied Piper of Hamelin (Boelter, 1909; Elton, 1942). The earliest recorded population irruption comes from the Old Testament of the Bible. Although rodents were not included in the ten plagues of Egypt, it is written that God punished the Philistines in a rodential way... "Mice were generated and 'boiled over' the towns and fields in the midst of that region, and there was a confusion of great death in the land" (Vulgate Bible, I Kings 5:6; Elton, 1942). The ancient Greeks also had to deal with rodent outbreaks, as Aristotle wrote, "The rate of propagation of field mice in country places, and the destruction they cause, are beyond telling. In many places their number is so incalculable that but very little of the corn–crop is left to the farmer" (Thompson, 1910; Elton, 1942). Populations can be extremely irruptive, as peak densities have been reported at 2500–200,000 rodents ha$^{-1}$ (Lantz, 1907; Hall, 1927; Elton, 1942). Such densities have led to widespread crop failures, as rodents have been known to attack all kinds of grain, forage, fruit, and vegetable crops at all stages of growth (Elton, 1942).

Prior to the development of chemical weed control,

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cropfields had high densities of non-crop plants that provided food to support rodent reproduction and overhead cover for protection from predators. With the advent of the "Green Revolution" in the early 1960s came the widespread use of effective herbicides and clean-farming practices that eliminated much of the in-field vegetation that used to support rodent populations. Agricultural rodent problems in developed countries diminished and were all but forgotten in North America.

Conservation tillage systems were developed and promoted largely in North America during the 1970s and 1980s, with the primary objective of reducing soil erosion through the management of crop residues. Typically 55–95% of the crop residue remains on the soil surface after conservation tillage operations, which helps to reduce wind and water erosion up to 96% (MidWest Plan Service, 2000). Unfortunately, conservation tillage systems have resurrected rodents as a major crop pest. Significant in-field populations of voles (*Microtus* spp.), field mice (*Peromyscus* spp.) kangaroo rats (*Dipodomys* spp.) and ground squirrels (*Spermophilus* spp.) have been reported recently (Hines et al., 1993; Corrigan and Hines, 1995; Hines and Hygnstrom, 2000). Most damage occurs when the rodents excavate and eat planted seeds and clip off emerging seedlings, usually before the fourth-leaf stage, resulting in significant stand loss and subsequent yield reductions. Reports of rodent damage to emerging corn seed and seedlings in conservation tillage fields have varied considerably: 80–100% in IL (Hines, 1993, 1997), 50–60% in IL (Beasley and McKibben, 1975, 1976); 20% in NE (Hygnstrom et al., 1996); 5–8% in NE (Holm, 1984); and 1% in IA (Young and Clark, 1984).

Some very rudimentary procedures have been used in the past to combat marauding hoards of rodents. A 16th century Latin account prescribed the following exorcism — 'Take a sheet of paper and write on it as follows, "I adjure you, ye mice here present, that ye neither injure me, nor suffer another mouse to do so. I give you yonder field" (here you specify a field, perhaps a neighbor's) "but if I catch you here again, by the mother of the gods, I will rend you in seven pieces." Write this and stick the paper on an unhewn stone in the field before sunrise, taking care to keep the written side uppermost' (Powell, 1929). Laws were passed that condemned rodents to death, and many farmers took it upon themselves to protect their fields with sticks, clubs, cats, dogs, guns, and poison (Elton, 1942). Several toxicants were used, but most fell into disfavor because of problems with availability, effectiveness, and environmental hazards. The last label clearance for use of a toxicant ($Zn_3P_2$) on rodents in cornfields was withdrawn by the United States Environmental Protection Agency (EPA) in 1989. At the time of our research (1992–1995), only habitat modification, alternative feeding, trapping, and border applications of toxicants were legal or recommended for in-field rodent control (Cleary and Craven, 1994; Howard, 1994; O'Brien, 1994; Timm and Howard, 1994). Unfortunately, most habitat modification procedures (grazing, burning, hay removal, tillage) are counterproductive to conservation tillage objectives. Alternative feeding methods may lead to increased rodent populations and have not been readily adopted by farmers. Most alternatives lack the consistent efficacy needed for cost-effective control.

Concern was expressed by the agricultural community regarding the potential impacts of rodents and other wildlife on crops planted in conservation tillage systems. In addition, rodenticide manufacturers provided the impetus for the development of a toxicant formulation that would be cost-effective and environmentally safe. Although $Zn_3P_2$ has been used to control rodents for nearly 60 years, relatively few reports are available on the efficacy of $Zn_3P_2$ for controlling mice or voles (Eisemann et al., 1999). In-furrow applications of granular insecticides can reduce the exposure of nontarget animals by up to 90% (EPA, 1992; RESOLVE Inc., 1994), but little is known about the efficacy of in-furrow applications of rodenticides; therefore, the authors conducted three independent experiments to determine the efficacy of in-furrow applications of 2% $Zn_3P_2$ pellets for controlling rodent damage to no-till corn. Although our methods differed, we feel our goals, study areas, materials, and results were consistent enough to warrant a meta-analysis and to highlight common conclusions.

## 2. Methods

### 2.1. Materials

We evaluated the in-furrow application of Hopkins® (now PROZAP®) Zinc Phosphide Pellets [2.0% active ingredient ($Zn_3P_2$); 98.0% inert ingredients (food-grade, milled, and processed cereal grains); HACO, Madison, WI, USA] in no-till corn. The pellets were relatively small (0.32 cm in diameter, 0.32 cm long), light (11,817 pellets $kg^{-1}$), and hard. The product was registered by EPA on 30 October 1997 as a Restricted Use Product (EPA Reg. No. 2393-521) to control rodents [e.g., meadow voles (*M. pennsylvanicus*), prairie voles (*M. ochrogaster*), house mice (*Mus musculus*), deer mice (*P. maniculatus*), white-footed mice (*P. leucopus*), thirteen-lined ground squirrels (*S. tridecemlineatus*), cotton rats (*Sigmodon hispidis*), Ord's kangaroo rats (*D. ordii*), banner-tail kangaroo rats (*D. spectabilis*), and Merriam's kangaroo rats (*D. merriami*)] in reduced-tillage and no-till corn. One in-furrow application can be made pre-planting or at-planting at a rate of 4.5–6.75 kg $ha^{-1}$ (4–6 lb $acre^{-1}$). The label allows for applications to entire fields, field perimeters, border rows, and spot treatments. The company's suggested retail price at the time of registration was US$2.75 $kg^{-1}$ (US$1.25 $lb^{-1}$) or US$12.40–US$18.50 $ha^{-1}$ (US$5.00–US$7.50 $acre^{-1}$), depending on application rate. Reference to this product is for identification purposes only — it does not imply endorsement and the exclusion of other products does not imply criticism.

$Zn_3P_2$ is an acute rodenticide. Its mode of action is by the release of phosphine gas ($PH_3$) during hydrolysis in the gastrointestinal tract of an animal that ingests $Zn_3P_2$ bait (Savarie, 1981; Marsh, 1984). Death in rodents results from $PH_3$-induced asphyxia and typically occurs within 30 h of ingestion (Timm, 1994). For rodents, the acute oral $LD_{50}$ ranged from a low of 5.6 mg $kg^{-1}$ for nutria to high 910 mg $kg^{-1}$ for Norway rats (Timm, 1994; HACO, 1996). $Zn_3P_2$ was also toxic to pheasants, ducks, geese, and domestic fowl ($LD_{50}$ — 7.5–35.7 mg $kg^{-1}$). The acute dermal $LD_{50}$ for rabbits was >2000 mg $kg^{-1}$. Crayfish, shrimp, and gobies tolerated 10–50 mg $kg^{-1}$ of $Zn_3P_2$ in water and crayfish readily consumed 1.88% $Zn_3P_2$-treated oat groat bait and survived. $Zn_3P_2$ deteriorates when exposed to environmental moisture and acids (Hilton and Robinson, 1972). It does not cause secondary poisoning because it decomposes rapidly in the gastrointestinal tract and it does not accumulate in the fat or muscle tissue of poisoned animals (Bell and Dimmick, 1975; Schitoskey, 1975; Savarie, 1981; Johnson and Fagerstone, 1994). In addition, toxicants are considered to be relatively safe when applied underground (Littrell, 1990).

### 2.2. Study areas

This project was conducted on three independent study areas, located at the Charles Paulsen farm near the University of Nebraska, Northeast Research and Extension Center in northeastern NE, the Taake Farm near the University of Illinois, Dixon Springs Agricultural Center in southern IL; and the Steve Lindaur Farm in Spencer County, southern IN.

#### 2.2.1. Nebraska

The Nebraska study was conducted during the summer of 1995 in a 64-ha field planted to bromegrass in 1986. The soil was Judson Silt Loam, which is a high silt, low organic matter soil that is relatively deep and well drained. We delineated a 5-m wide, 500-m long strip in an east–west direction in the northern half of the bromegrass field. The strip was shredded with a rotary mower to a height of 10 cm on 6 June 1995. We planted four rows of Pioneer 3394, 110-day field corn to the strip, using a no-till planter on 8 June 1995. The corn was planted at a row spacing of 76 cm and density of 48,000 kernels $ha^{-1}$ (3.7 kernels $m^{-1}$ of row). A post-emergence herbicide (Extrazine, 16.5 kg $ha^{-1}$) was applied to the corn on 20 June 1995. Cornfields in NE are typically planted in early- to mid-May to take advantage of the long growing season. We delayed corn planting 1 month due to excessive rainfall (10 cm above normal) and relatively low mean soil and ambient temperatures (6 and 3°C below normal, respectively), during May 1995.

#### 2.2.2. Indiana

We conducted the study during the summer of 1995 in a 12-ha field that was previously wheat, double cropped with soybeans. The soil was Alford Silt Loam, which is a high silt, low organic matter soil that is relatively deep and well drained. We planted Pioneer 3394 corn using a no-till planter on 6 June 1995 at a row spacing of 76 cm and density of 60,000 kernels $ha^{-1}$. We made one application of pre-plant herbicides, including Extrazine II (6.5 l $ha^{-1}$) and AAtrex Nine-O (0.57 kg $ha^{-1}$) and one post-emergence application of Beacon (0.03 l $ha^{-1}$) and Accent (0.01 l $ha^{-1}$). Most cornfields in Indiana are planted in early May to take advantage of the long growing season. As in the Nebraska study, we delayed corn planting a month because an excess of 38 cm of rainfall occurred during April and May.

#### 2.2.3. Illinois

The Illinois study was conducted during the summers of 1992–1994. In 1992, we used a 14-ha field of KY 31 tall fescue, established in 1990. Half of the field was mowed to a height of 10 cm in August 1991 and half was left unmowed. The soil was a Hosmer Silt Loam, which is a high silt soil that is relatively deep and well drained, with 2.0% organic matter and pH of 7.0. We planted Pioneer 3379 field corn throughout the field at a density of 61,774 kernels $ha^{-1}$ and row spacing of 76 cm with a no-till planter on 6 May 1992. We applied Agrox D-L Plus as a seed treatment and Lorsban 15G (9.8 kg $ha^{-1}$) in-furrow at planting to control damage caused by insects. Shortly after planting, we used a Hardy sprayer with flat-fan nozzles on a 12.2-m boom to spray a tank mix of water and the following pre-emergence herbicides: AAtrex 4L (1.17 l $ha^{-1}$), Bullet 4ME (9.35 l $ha^{-1}$), Weedone LV4 (1.17 l $ha^{-1}$); Gamoxone Extra (2.34 l $ha^{-1}$), and Activator 90 (2.34 l $ha^{-1}$). In addition, we applied Pounce 3.2EC (0.29 l $ha^{-1}$) to control damage caused by insects. In 1993, we used a 10-ha field of hairy vetch, that was no-till planted into wheat stubble in 1992. The soil was an Alford Silt Loam, which is a high silt soil that is relatively deep and well drained, with 3.2% organic matter and pH of 6.4. We planted Pioneer 3394 field corn throughout the field at a density of 66,716 kernels $ha^{-1}$ and row spacing of 76 cm with a no-till planter on 28 May 1993. Insect and weed control applications were the same as those made in 1992. In 1994, we used another 8-ha field of hairy vetch, that was no-till planted into wheat stubble in 1993. The soil was a Hosmer Silt Loam, with 2.9% organic matter and pH of 6.2. We planted Pioneer 3394 field corn throughout the field at a density of 60,539 kernels $ha^{-1}$ and row spacing of 76 cm with a no-till planter on 24 May 1994. Insect and weed control applications were the same as those made in 1992 and 1993.

### 2.3. Methods

We tested the effectiveness of in-furrow applications of 2% $Zn_3P_2$ pellets for reducing rodent damage in no-till corn in three independent studies using different methods.

#### 2.3.1. Nebraska

Experimental treatments were randomly assigned to the 500-m strip of no-till corn by 10-m plots within 40-m blocks. We applied 27.5 kg $ha^{-1}$ (5 lb $acre^{-1}$) of $Zn_3P_2$ pellets in-furrow to every fourth 10-m plot at planting with a Gandy row applicator mounted on a John Deere planter. Immediately after planting, we installed one 2.2-m × 0.25-m welded wire exclosure over each of the four corn rows within the second and fourth 10-m plots of each 40-m block. The exclosures were randomly located within the 10-m rows. The untreated 10-m plots that were located between the 10-m treatment plots served as buffers to reduce dependence among adjacent treatment plots. Our resultant experimental design consisted of 10 replicates of four treatments, in decreasing order of protection from rodent damage: zinc phosphide-exclosure (ZP-E); no zinc phosphide-exclosure (NZP-E); zinc phosphide-no exclosure (ZP-NE); and no zinc phosphide-no exclosure (NZP-NE). Since our primary interest was plant emergence, we used the number of emerging corn plants $m\text{-of-row}^{-1}$ as a response variable to determine the effectiveness of the treatments. On 9 July 1995, when the corn plants were at the third- to fourth-leaf stage, we counted the number of plants emerged in a 2-m-of-row plot located within each exclosure and two 2-m-of-row plots located outside of each exclosure. The same procedure was repeated for treatments without exclosures. No effort was made to distinguish between rodent and bird damage in the corn rows. The amount of bird damage was likely negligible. We used a two-factor split plot design and analysis of variance (Hays, 1963; Wilkinson, 1989) to test the null hypothesis:

$$Y_{\text{ZP-E}} = Y_{\text{NZP-E}} = Y_{\text{ZP-NE}} = Y_{\text{NZP-NE}}$$

where, $Y$ equals the mean number of emerged corn plants $m\text{-of-row}^{-1}$.

To provide an indirect measure of rodent pressure on the corn seed and seedlings, we set out 400 Victor® Museum Special snap traps that were baited with peanut butter for a 12-h period, the night before the exclosures were removed and plants were counted. Two 500-m transects were located in the untreated bromegrass, parallel to and 5 and 10 m away from the north edge of the four-row strip of corn. Two other transects were located in a similar fashion from the south edge of the corn strip. One-hundred snap traps were placed 5 m apart on each transect. Standard techniques were used to minimize exposure of researchers to hantavirus (Centers for Disease Control and Prevention, 1993). This project was approved by the University of Nebraska Institutional Animal Care and Use Committee (IACUC # 95-06-038).

#### 2.3.2. Indiana

Two treatments were evaluated in four replications of a completely randomized design. We applied 27.5 kg $ha^{-1}$ (5 lb $acre^{-1}$) of $Zn_3P_2$ pellets in-furrow to four plots at planting with a Gandy applicator mounted on a John Deere planter. The plots were 12 rows wide (9.1 m) and 366 m long. Four untreated plots of a similar size served as controls. We determined plant densities by counting the corn plants during the sixth-leaf stage in three sites (10.6 $m\text{-of-row}^{-1}$) and shortly before harvest in two sites (21.2 $m\text{-of-row}^{-1}$) that were randomly located within each of the treatment and control plots. Yields were measured by harvesting a strip of corn eight rows wide (6.1 m) and 266.5 m long from within each of the plots. Grain moisture at harvest averaged 20.0% and the calculated yield was corrected to 15.5% moisture. We determined an average rodent density by searching the plots in April 1995 and counting the number of colonies (indicated by proximate vole burrows and associated runways). Snap traps were used to capture individuals for species identification. The data were analyzed using a two-level analysis of variance.

#### 2.3.3. Illinois

We randomly located three 12.2-m × 42.7-m plots per treatment in each of the fields during the 1992, 1993, and 1994 field seasons. In addition to the year and field type (unmowed tall fescue, mowed tall fescue, and hairy vetch), we included the following treatments: in-furrow $Zn_3P_2$; broadcast whole-kernel corn; broadcast cracked corn, early pre-plant herbicide; and pre-emergence herbicide (control). We applied $Zn_3P_2$ pellets (27.5 kg $ha^{-1}$ [5 lb $acre^{-1}$]) in-furrow in each of three plots each year, with a Gandy applicator at planting. We used a 4-ton double-fan fertilizer buggy to broadcast whole-kernel corn (125.5 kg $ha^{-1}$ [2 bushels acre$^{-1}$]) and cracked corn (251.0 kg ha$^{-1}$ [4 bushels acre$^{-1}$]) to their respective plots 24 h before planting. Early pre-plant herbicides (same materials and application rates as the pre-emergence applications) were applied 21–30 days before planting. The control plots received no treatment other than the pre-emergence herbicides that were applied to all of the study fields. We counted the number of corn plants and determined the corn yield in each of the treatment and control plots in late-September and early-October. We calculated the percentage of plants damaged by voles ha$^{-1}$ by comparing the plant population at the beginning and the end of the field season. We searched the treatment and control plots in late-March and early-April and counted the number of active vole colonies. Since the data were similar across years and field types ($P = 0.05$), we pooled the data. The data were analyzed using an analysis of variance and Duncan's multiple range test ($P = 0.05$).

## 3. Results and discussion

### 3.1. Nebraska

The mean corn plant density in unprotected plots (NZP-NE, $\bar{x} = 1.92$ plants m$^{-1}$) was 20% less than the mean density in plots protected with welded wire exclosures (NZP-E, $\bar{x} = 2.40$ plants m$^{-1}$, Table 1). Plots with in-furrow applications of 2% $Zn_3P_2$ pellets also appeared to have higher (12%) corn plant densities (ZP-NE, $\bar{x} = 2.19$ plants m$^{-1}$). Differences among the treatments, however, were not statistically significant ($P = 0.76$) because of the variability among individual sample plots (range = 0–5 plants, $n = 120$). We observed no differences in damage levels across the four rows ($P = 0.63$), and therefore, assume that the rows were equally available to the voles (no edge effect). Although not statistically significant, we feel that a 10–20% decrease in crop yield would be economically significant to most producers. Independent research on landowner attitudes has frequently identified landowner tolerance levels of wildlife damage at about 15% of crop yield (Craven et al., 1992). In a representative 64-ha cornfield, yield loss to rodent damage would equal US$3200 versus US$1920 in a field protected by $Zn_3P_2$, assuming a net profit of US$250 ha$^{-1}$. The material and labor cost for applying the $Zn_3P_2$ (using Illinois figures, Table 2) would be US$950, resulting in a benefit:cost ratio of 1.3:1, which provides little economic justification for applying $Zn_3P_2$ when the rodent population is low.

The most frequently captured small mammal species during the 400 trap-night period was the deer mouse ($n = 18$). No voles were captured during the trapping period even though several were observed in the study area in November 1994. Our overall capture rate was only 6.7 captures 100-trapnights$^{-1}$ versus 14.6 captures 100-trapnights$^{-1}$ in no-till cornfields in NE (Holm, 1984). We suspect that field rodent populations declined during the winter preceeding the study due to normal mortality factors and recruitment in spring was inhibited by near-record low temperatures and high rainfall. As a result, rodent pressure on the treatments was not as high as expected. In addition, corn planted late in the season typically emerges and grows quickly once the weather warms up, resulting in a shorter period that the seeds and emerging plants are susceptible to damage by small rodents.

Table 1
Mean number of corn plants m-of-row$^{-1}$ that emerged in a no-till cornfield[a], relative to four treatments applied to protect against rodent damage [zinc phosphide-exclosure (ZP-E), no zinc phosphide-exclosure (NZP-E), zinc phosphide-no exclosure (ZP-NE), and no zinc phosphide-no exclosure (NZP-NE)] in northeastern NE, 1995

| Treatment | $n$ | $\bar{x}$ | SE |
|---|---|---|---|
| ZP-E | 40 | 2.34 | 0.17 |
| NZP-E | 40 | 2.40 | 0.17 |
| ZP-NE | 80 | 2.19 | 0.12 |
| NZP-NE | 80 | 1.92 | 0.12 |

[a] Planted into mowed smooth bromegrass established in 1986.

### 3.2. Indiana

At the sixth-leaf stage, the plant population in the $Zn_3P_2$ plots (55,172 plants ha$^{-1}$) was 9% higher than in the untreated plots (50,971 plants ha$^{-1}$, $P = 0.01$). At harvest, treated plots yielded 7% more corn than control plots (8662 versus 8097 kg ha$^{-1}$, $P = 0.01$). In a representative 64-ha cornfield, such a difference would result in the loss of about US$1,044, assuming a net profit of US$250 ha$^{-1}$. The costs of the $Zn_3P_2$ application would again equal US$950, resulting in a benefit:cost ratio of 1.1:1, which is relatively low.

Rodent surveys conducted in early April revealed a mean of 62 active vole colonies ha$^{-1}$ in the study area before the corn was planted. Trapping confirmed the presence of meadow voles and deer mice. The area received 38 cm of rainfall, however, during April and May, which appeared to reduce the rodent population or feeding activity. In addition, the corn was planted late in the season, and therefore, was less susceptible to damage by small rodents.

### 3.3. Illinois

The vole populations in the Illinois treatment plots were relatively high, with the mean number of active vole colonies ranging from 104 to 138 colonies ha$^{-1}$ (Table 2). Although the control plots had the lowest vole population levels, they sustained the highest mean standard reduction (45%) and the lowest mean corn yield (6590 kg ha$^{-1}$) of all the treatments ($P = 0.05$). While mean vole populations were highest in the $Zn_3P_2$ treatment plots at the beginning of the study, standard reduction and yield loss was lower than in the control plots ($P = 0.05$). Since we did not measure the vole populations after the treatments were applied, we must speculate that the $Zn_3P_2$ led to a reduction in the vole population and thus, a reduction in the damage. Corn yields in the controls were 34% lower than those in the $Zn_3P_2$ treatments. In a representative 64-ha field, such a difference in yield would result in the loss of about US$5360, assuming a net profit of US$250 ha$^{-1}$. The costs of the $Zn_3P_2$ application would again equal US$950, resulting in a benefit:cost ratio of 5.6:1, which provides considerable economic justification for applying $Zn_3P_2$ when populations of field rodent are high.

The most effective treatment for reducing rodent damage in the Illinois study was the application of pre-plant herbicides 21–28 days before planting (Table 2). The early pre-plant herbicides resulted in the reduction of the vole habitat before planting. Although we did not survey post-application vole populations, it appeared that the voles vacated the treated plots and sought refuge in areas with more substantial food and cover. The early pre-plant herbicide treatment was the least expensive (Table 2) and easiest to apply, since the field was already scheduled for an herbicide application. Although the use of pre-plant herbicides in no-till systems is common, some producers prefer to use cultural methods such as mowing, grazing, or fire. In addition, others may not rent fields or make planting decisions until it is too late to apply early pre-plant herbicides.

The broadcast application of whole-kernel corn effectively reduced damage in the treatment plots. When applied 24 h before planting, the readily-available corn bait served as a lure crop, that diverted the feeding behavior of rodents from planted corn kernels and resultant seedlings. The application of 125.5 kg ha$^{-1}$ (2 bushels acre$^{-1}$) of whole-kernel corn was relatively inexpensive (Table 2) and did not lead to problems with excessive germination and growth of the bait (volunteer corn).

### 3.4. General use and effectiveness of in-furrow applications of $Zn_3P_2$ pellets

In all three studies, rodents damaged no-till corn less in areas that received in-furrow applications of $Zn_3P_2$ pellets. Decades earlier, Beasley and McKibben (1975) reported significant reductions in vole damage (38% versus 7%) in no-till corn after an in-furrow application of $Zn_3P_2$-treated bait, even under the pressure of high vole populations. Variations in the effectiveness of any control method can be expected when working with rodents in field crops because of differences in rodent population levels and behavior and changes in weather and habitat. The unusually high rainfall in the spring of 1995 appeared to reduce the rodent populations or their feeding activity in the Nebraska and Indiana studies, which resulted in diminished levels of damage. Benefit:cost ratios in our studies increased dramatically as the on-site vole populations increased. $Zn_3P_2$ applications would have been only marginally cost-effective in the Nebraska and Indiana study areas, but they would have been easy to justify economically in the Illinois study area. These results reinforce the need for in-field pest population monitoring and scientifically-based economic thresholds.

In-furrow applications of pesticides reduce the risk of exposure to nontarget animals (EPA, 1992;

Table 2
Mean vole populations, crop damage, and control costs in no-till cornfields[a] relative to five rodent control treatments[b] in southern IL, 1992–1994

| Treatment | Active colonies ha$^{-1}$ | Corn plants ha$^{-1}$ | Percent damaged | Corn yield (kg ha$^{-1}$) | Cost (US$ ha$^{-1}$) |
|---|---|---|---|---|---|
| Early pre-plant herbicides | 116 a[c] | 57062 a | 6 c | 10545 a | 0.00 |
| Whole-kernel corn | 114 a | 55772 a | 8 c | 9980 a | 14.86 |
| Zinc phosphide | 138 a | 52980 ab | 13 bc | 9917 a | 14.82 |
| Cracked corn | 111 a | 49783 b | 18 b | 9792 a | 32.12 |
| Untreated control | 104 a | 33316 c | 45 a | 6590 b | 0.00 |

[a] 1992 — mowed and unmowed KY 31 tall fescue established in 1990.
1993 — hairy vetch seeded after wheat in 1992.
1994 — hairy vetch seeded after wheat in 1993.

[b] Early pre-plant herbicides — only pre-emergence herbicides applied 21–28 days before planting instead of at planting.
Whole-kernel corn — broadcast at 125.5 kg ha$^{-1}$ (2 bushels acre$^{-1}$) 24 h before planting, plus pre-emergence herbicides applied at planting.
Cracked corn — broadcast at 251 kg ha$^{-1}$ (4 bushels acre$^{-1}$) 24 h before planting, plus pre-emergence herbicides applied at planting.
Zinc phosphide — 2% pellets applied in-furrow at 27.5 kg ha$^{-1}$ (5 lb acre$^{-1}$) at planting, plus pre-emergence herbicides applied at planting.
Untreated control — only pre-emergence herbicides applied at planting.

[c] Treatment means followed by the same letter do not differ significantly ($P = 0.05$, Duncan's MRT).

RESOLVE Inc., 1994), and therefore, should be encouraged, especially if efficacy is not reduced. Although we did not specifically look for impacted nontarget animals, none were observed in our study areas. In-furrow application of $Zn_3P_2$ pellets does require specialized equipment and additional labor. The meters inside conventional insecticide boxes cannot be used because the rollers will crush the pellets, resulting in an ineffective product and inappropriate application rates. We recommend one of the following approaches for proper in-furrow application of $Zn_3P_2$ pellets: (1) calibrate a planter and simply plant the pellets prior to planting the crop; (2) retrofit the insecticide boxes on the existing planter with metering rotors (Positive Placement Kits, Ag Resources, AR, WI, USA, ≈US$50 row$^{-1}$); or (3) attach Gandy Positive Displacement Row Applicators to the existing planter (with the half-rate chemical wheels and spacers installed, Gandy Company, Owatonna, MN, USA, ≈US$350 row$^{-1}$).

Rodenticide manufacturers have explored the use of pelletized baits because they are generally more resistant to environmental degradation, easier to use, and possibly more attractive to the target pest species. Byers and Carbaugh (1987) reported that ZP Rodent Bait AG pellets yielded higher mortality rates than $Zn_3P_2$-treated whole wheat, cracked corn, or another pelletized formulation. $Zn_3P_2$ pelletized baits were 30% more effective in controlling pine and meadow voles than $Zn_3P_2$-treated corn and oats (Byers et al., 1982). In addition, Merson and Byers (1981) reported that 2% $Zn_3P_2$ pellets produced significantly quicker and higher levels of mortality than a $Zn_3P_2$-treated oat-corn bait. Whole oat and cracked corn baits performed as well as the pelletized bait. We found the Hopkins® (PROZAP®) Zinc Phosphide Pellets to be easy to use and effective in reducing rodent damage in no-till corn.

All of the experimental plots in the Illinois study were subjected to the combined effects of two or three control methods: first, by the modification of habitat through the pre-emergence herbicides; second, by the mowing of vegetation; and third, by the action of the specific treatment agent. Stand reduction in the $Zn_3P_2$ treatment plots was less in the mowed tall fescue (6%) than in the unmowed tall fescue (12%) and hairy vetch plots (17%). The benefits of integrated control methods have also been highlighted by Hunter et al. (1987) who reported that the efficacy of $Zn_3P_2$ baits for controlling voles damage in apple orchards was increased when used in combination with surface raking. The raking disturbed the aboveground vegetation that voles used for food and shelter.

## 4. Management recommendations

Managers should use an integrated pest management (IPM) approach to prevent rodent damage problems in conservation tillage systems. IPM incorporates the proper identification of crop pests, population monitoring, and the timely use of a variety of cost-effective methods to reduce damage to a tolerable level. Seldom will any single method eliminate damage. We recommend the following approach to reduce impacts of rodents on corn in conservation tillage systems:

1. inspect fields in late-March for active rodent colonies;
2. apply early pre-plant herbicides about 1 month before planting if more than 12 active vole colonies ha$^{-1}$ are located;
3. inspect fields again for active rodent colonies one week before planting — if more than 12 active vole colonies ha$^{-1}$ are located again;
4. broadcast 125 kg ha$^{-1}$ of whole kernel (2 bushels acre$^{-1}$) 24 h before planting; or
5. apply 4.5–6.75 kg ha$^{-1}$ (4–6 lb acre$^{-1}$) of $Zn_3P_2$ pellets in-furrow at planting.

$Zn_3P_2$ is most useful in fields with high rodent densities and where managers cannot access the field before planting because of weather, field conditions or other work priorities. We recommend in-furrow applications of $Zn_3P_2$ pellets to minimize exposure to non-target animals. Additional precautions to protect endangered species, wildlife, livestock, pets, and humans are included in the pesticide label.

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